

I. EXECUTIVE SUMMARY

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Infrared astronomy is on the threshold of a revolution. The decade of the 1990's presents an unparalleled opportunity to address fundamental astrophysics issues through observations at infrared wavelengths (1 μm to 1000 μm) made possible by enormous technological and scientific advances during the last decade. The formation of galaxies, stars and planets, the origin of quasars, and the nature of active galactic nuclei are among the key scientific issues to be addressed by these observations.

The major elements of the recommended program are:

THE SPACE INFRARED TELESCOPE FACILITY (SIRTF)

SIRTF is the single most important new astronomy project for the 1990's. A cryogenically cooled space observatory of 5 years lifetime, SIRTF will complete NASA's Great Observatories program by enabling observations across the 3 μm to 700 μm region with a sensitivity gain of 2 to 4 orders of magnitude over all current capabilities. SIRTF will redefine the state-of-the-art in infrared exploration of the universe.

THE STRATOSPHERIC OBSERVATORY FOR INFRARED ASTRONOMY (SOFIA) & THE IR OPTIMIZED 8-M TELESCOPE (IRO)

SOFIA, a 2.5-m telescope system in a modified Boeing 747 aircraft, utilizes the airborne environment to observe free from most of the absorption by telluric water vapor.

IRO, a national 8-m telescope fully optimized for infrared observations, exploits the remarkably dry and stable atmospheric conditions of the summit of Mauna Kea.

Together, SOFIA and IRO span the IR at high angular resolution with more than an order of magnitude increase in sensitivity compared to current ambient temperature telescopes. SOFIA and IRO will complement SIRTF by their ability to achieve higher spectral and spatial resolution, by their long lifetime, and by their ability to support evolving instrumentation.

Other highlights of this report include:

A DETECTOR AND INSTRUMENTATION PROGRAM

A vigorous, broadly based IR array detector development, evaluation and implementation program to exploit the revolution in IR array technology and recent advances in adaptive optics.

THE SUBMILLIMETER MISSION (SMMM)

An Explorer-class space experiment to obtain an unbiased spectral line survey of the rich 100 μm to 700 μm region.

THE 2 μm ALL SKY SURVEY (2MASS)

An all-sky three-color survey in the 1 μm to 2.5 μm region, reaching 50,000 times fainter than the existing two micron sky survey. Key issues in the structure of the local universe and the large scale structure of the Galaxy will be addressed.

A SOUND INFRASTRUCTURE

A strong base of support for laboratory and theoretical astrophysics, for the development of well trained instrumentalists through airborne and ground-based observational programs and for archival data analysis programs.

TECHNOLOGY DEVELOPMENT PROGRAMS

An active technology program directed towards the further exploitation of the space environment for far-IR/submm astronomy, and a ground-based imaging interferometry program leading to an optical/infrared VLA in the next decade.

II. PERSPECTIVE

How do stars and solar systems form? How does material synthesized in stellar cores enrich the interstellar medium and alter the subsequent evolution of stars and planets? Why do new stars form at such a dramatic rate in some galaxies? What produces the exotic behavior in the nucleus of our Galaxy, and is this activity related to the far more powerful QSO phenomenon? What are the sources of cosmological background radiations? How and when did the first stars and galaxies in the Universe form? From the sensitive probing of the first seeds of structure in the Universe, to exploring the nature of the processes that shape star and planetary system formation, observations in the IR address questions that form the basis for modern astrophysical inquiry.

Four physical principles underscore the critical role played by infrared observations in addressing these questions.

IR observations uniquely reveal cool states of matter.

The most common stars are cooler than the Sun, and emit much of their energy in the infrared. The Earth and other planets, including those around other stars, emit most of their radiant energy in the IR. Star-forming regions and massive interstellar clouds are cooler still, radiating essentially all their energy in the IR.

IR observations explore the hidden Universe.

Ubiquitous cosmic dust, an efficient absorber of optical and ultraviolet radiation, becomes increasingly transparent in the IR, where it re-emits the bulk of its absorbed energy. This is dramatically illustrated in the frontispiece. Our galaxy is transparent at mid-IR wavelengths, while optical radiation from the Galactic Center is attenuated by a factor of about a thousand billion.

IR observations access a wealth of spectral features.

Spectral features of atoms, ions, and virtually all molecules and solids are located within the IR. These features probe the conditions in celestial regions as diverse as the shocks in supernova remnants, obscured stars and the nuclei of galaxies, the atmospheres of planets, the cold interiors of dark clouds, and the circumstellar disks which contain the raw material of planets. The emitting material in these sources ranges from condensed forms of matter like ices and silicates to highly ionized gases and from that most abundant of simple molecules, molecular hydrogen, to highly complex hydrocarbons.

IR observations reach back to the early life of the cosmos.

The expansion of the universe inexorably shifts energy to longer wavelengths. The primeval fireball of high energy gamma rays produced in the Big Bang now appears as 2.74K blackbody emission that peaks near 1000 μm . Most of the energy emitted from stars, galaxies, and quasars since the beginning of time now lies in the infrared. How and when the first objects in the universe formed will ultimately be determined by infrared observations.

These four principles make infrared observations crucial to the solution of the most pressing problems of modern astrophysics. Technological advances during the 1980's revolutionized our ability to exploit the potential of the infrared, while the scientific advances of the decade profoundly changed our view of the sky. Major highlights included:

The successful deployment of cryogenically-cooled telescopes in space.

The Infrared Astronomical Satellite (IRAS) and Cosmic Background Explorer (COBE) missions, developed as part of NASA's Explorer program, achieved enormous gains in sensitivity through a million-fold reduction in the level of background radiation using liquid-helium (LHe) cooled telescopes and instruments which demonstrated the fundamental technology required for exploiting the environment outside the earth's atmosphere.

The 1983 IRAS sky survey, a joint U.S./Netherlands/United Kingdom project, revealed for the first time the richness and variety of the IR sky. It laid the foundation for major scientific advances, impacted all fields of astrophysical research, and made IR observations accessible to the whole astronomical community; about 70% of the IRAS data users are other than infrared astronomers.

IRAS discovered disks of particles orbiting nearby mature stars. These disks, first discovered by studying the bright star Vega, appear closely related to the evolution of planetary systems, and may be debris of the planet accumulation process. IRAS also discovered dust bands in our solar system that appear to be debris of asteroid

collisions, a likely source of the bulk of the zodiacal dust grains. The IRAS observations of hidden clusters of young stars and protostars in dark clouds throughout the Milky Way provided the first census of the luminous stellar content in these stellar nurseries. IRAS discovered structured emission from interstellar grains (termed "IR cirrus") that may be produced in part by large complex hydrocarbon molecules, a major new component of the interstellar medium.

IRAS found IR-bright galaxies, galaxies emitting more than 99% of their luminosity in the IR, radiating 1000 times or more the energy output of the Milky Way. These galaxies are more numerous than QSO's of the same luminosity, and may represent an early stage of QSO evolution. Because of their relatively high space density, their high luminosity, and their apparent link to systems undergoing collisions or mergers, ultra-luminous IR galaxies are potentially powerful tracers of luminous matter out to the edge of the Universe.

COBE, launched in November 1989, is in the process of transforming our understanding of the early Universe by collecting data on the infrared, submillimeter and microwave diffuse emission in space. Early in its life, COBE demonstrated precise agreement between the observed Cosmic Background Radiation and a 2.74K blackbody. This result severely constrains models of the early Universe, and rules out a uniform hot intergalactic medium as the source of the X-ray background. The COBE instruments will be remarkably sensitive probes of the important processes in the early universe, and may reveal the first seeds of structure in the Universe and evidence of the epoch of galaxy formation.

A million-fold improvement in the performance of IR detectors.

The recent development in the US of large-format high-performance infrared sensitive arrays promises to make both cryogenic and ambient-temperature IR telescopes millions of times more capable than their predecessors of a few years ago. Each pixel of a modern IR array is some 10 to 100 times more sensitive than previous single detectors. Combined with the increased format, the gain in "speed" can be 10^7 to 10^9 , making possible qualitatively new approaches to instrumentation design and use, thereby enabling entirely new classes of scientific investigations. In their infancy these arrays have already been utilized to image a wide range of environments, such as probing for stars forming in the nearest clouds (Figure 1) and searching the extragalactic sky for very distant galaxies (c.f. Figure 6). A few years ago, the 2.2 μ m image in Figure 1 would have required mapping with a single detector, taking many nights to complete; only a few minutes were required with a camera based on modern IR array technology.

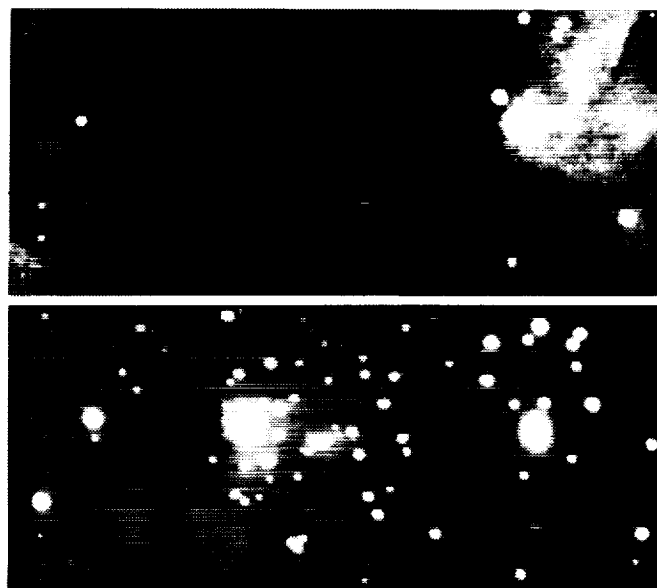


Fig. 1. Images of the star formation region NGC2024; 0.7 μ m (top) and 2.2 μ m (bottom), revealing young embedded stars in the IR. Courtesy of R. Probst, KPNO

Exploration of new phenomena through the flexibility of the airborne astronomy program.

IR observations from an altitude of 41,000 feet and above liberate us from many of the limitations imposed by atmospheric absorption. For the past 15 years, NASA's Kuiper Airborne Observatory (KAO) has been a showcase for the wealth of phenomena that can be observed from a mobile stratospheric platform. These include the discovery of the torus of gas and dust around the Galactic Center, the first observation of the water molecule in comets, and the first direct estimates of the masses of Fe, Co, and Ni in Supernova 1987A in the Large Magellanic Cloud.

The last decade has resulted in an explosion in the breadth and depth of our investigations of the infrared sky, driven by the initial exploitation of infrared observations from the space environment and by advances in the technical maturity of infrared detectors and associated instrumentation. Observational infrared astronomy is now poised to revolutionize our understanding of the most fundamental questions of modern astronomy.

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III. SCIENCE OPPORTUNITIES

A. THE ORIGIN OF GALAXIES

How did homogeneously distributed matter in the early universe condense into galaxies? To address this question empirically we must observe the galaxy formation epoch, then trace the development of large scale structure in the distribution of galaxies as a function of redshift. We must understand how individual galaxies relate to the processes that explain these structures, and on a more local scale, we must fit the details of our own Galaxy into this overview.

How do cosmic backgrounds relate to the large scale structure of the universe?

Results from the COBE mission will provide an initial opportunity to look for evidence of primordial galaxy formation. The COBE all sky maps from 1 μm to 1 cm will be the first step toward a determination of the true cosmological background radiation. The best windows on the extragalactic universe are at 3 μm to 4 μm , between the scattered and re-radiated components of the zodiacal dust, and at 200 μm to 500 μm , between the thermal emission from Galactic dust and the cosmic microwave background. These windows are the most promising in the entire electromagnetic spectrum for the detection of radiation from primordial galaxy formation. Such radiation can provide cosmological information even in the absence of observations of individual primordial galaxies. Extragalactic infrared backgrounds can set important limits on the epoch and nature of galaxy formation as long as known galaxies at lower redshifts are accurately subtracted. This requires accurate knowledge of all populations contributing to the backgrounds. These populations will be accounted for by the infrared surveys of the 1990's. Folding in the deep source counts of near-IR and mid-IR observations, combined with estimates of their contributions in the far-IR should allow us to tell unambiguously if infrared background radiations arise from the glow of the universe at the time galaxies first formed.

Infrared sky surveys in the 1990's will be essential to probe the distribution of matter in the nearby universe. The near infrared is the optimum region to obtain a mass census of galaxies because infrared radiation is both insensitive to the extinction within galaxies (including our own) and sensitive to the stellar component which dominates the luminous mass. The "great attractor", for example, is in a direction greatly affected by obscuration from the Milky Way Galaxy. Any mass concentration there may be detectable only in the infrared. Infrared observations will be the only way to detect cool, solid objects in galaxy halos. Systematic observations of galaxies with old stellar populations and the deepest possible searches for faint matter are essential to understand the mass distribution in large scale structures.

When did galaxies form?

Recent observations in the optical have established that the epoch of initial nucleosynthesis, star formation, and galaxy formation is at a sufficiently high redshift that the initial formation epoch can only be observed in the infrared, because the redshift must be greater than 5. Pushing back the limits on this formation epoch, or finding it, is a major imperative for observational extragalactic astronomy.

A quasar is now known at a redshift of nearly 5. If a significant population of quasars exists much beyond this, such a population cannot be measured without observations in the near infrared. Although quasars currently represent the highest redshift objects observed, their relation to primordial galaxy formation is unknown because their ultimate luminosity sources seem unrelated to stars. Direct evidence, or limits on the existence of galaxies made of stars, is also an observational requirement before the formation of stars and galaxies in the early universe can be understood. Determination of a redshift based on the bluest line, Lyman alpha, requires infrared spectroscopy for redshifts greater than 7, while observations of the old stellar population require measurements at wavelengths of about $(1+z)$ μm .

Such observations of old stellar populations in distant galaxies will set limits on the epoch of star formation in the universe, but direct observation of the first generation of star formation is the ultimate goal. Depending on the redshift of the formation epoch, near to mid-infrared observations will be required to detect the intrinsic ultraviolet luminosity from hot, young stars. IR observations have already demonstrated that extensive star formation in local galaxies is invariably accompanied by dust absorption at UV and optical wavelengths and re-emission in the IR. Is this the case also at high redshift epochs? Will HST observations of young galaxies at great distances be affected by dust attenuating the ultraviolet continuum?

What energy sources power galaxies?

One of the most significant discoveries of the 1980's was that of ultra-luminous IR galaxies, systems in which some process - perhaps starbursts or accretion by massive black holes - produces enormous infrared luminosities on a scale previously identified only with quasars. IRAS survey results suggest that this energetic activity correlates with galaxy interactions or mergers. Such luminous targets can be traced all the way back to the formation epoch with observations in the 1990's. Comparison of infrared luminosity distributions with those measured from other surveys, particularly in X-ray or ultraviolet radiation, is essential to account for luminous galaxies and quasars otherwise overlooked because of obscuration.

What is the distribution of matter in the Milky Way and nearby galaxies?

The evolution of galaxies is marked by a continuing cycle of birth and death of stars. This leads to the evolution of the elements from nearly pure hydrogen and helium to material with sufficient heavy elements to form earth-like planets. IR studies out to the distance of the Virgo cluster and beyond will measure elemental and chemical abundances of many of the heavy elements, both in the reservoir of the interstellar medium and as newly-formed material ejected from supernovae, novae and red giant stars. The age, composition, and structure for our Galaxy are crucial benchmarks for understanding other galaxies. Our vantage point is immersed in the obscuring dust of the Galactic disk, but infrared observations allow us to penetrate the dust in order to study stars and interstellar matter throughout the Galaxy. IRAS far-IR and COBE near-IR images of the sky toward the Galactic center, together with a visual view, are displayed as the frontispiece of this report. The COBE and IRAS images show the distribution of stars and luminous dust clouds, respectively, in this region of sky - extraordinary demonstrations of the power of infrared observations to reveal the grand design of the Milky Way Galaxy.

B. THE ORIGIN OF PLANETS, PLANETARY SYSTEMS AND STARS

The essential questions concerning star and planet formation, processes which are central to our concept of the universe in which we live, remain unanswered. Most of the visible matter in the Universe is in the form of stars, and star formation is central to the formation and evolution of galaxies. Closer to home, the formation of planets and planetary systems is a prerequisite for the formation of life as we know it. Both of these birth processes occur deep within dense clouds of dust and gas opaque at visible wavelengths but transparent in the infrared.

How do stars form, and what conditions lead to protostellar collapse?

Star and planet formation begins with a dense molecular cloud core which collapses to form a protostar embedded in a circumstellar protoplanetary disk. The protostar grows by direct infall of material onto the star and by accretion from the inner boundary of the disk. The gas and dust remaining in the disk is the raw material from which planets form.

The rate at which stars form and the resultant distribution of stellar masses must depend on the physical properties of the molecular cloud; composition, gas density, temperature, velocity field, chemical and ionization state, and magnetic field. In the 1990's we will image molecular clouds with sufficient sensitivity, spatial resolution and spectral resolving power to measure the conditions throughout star-forming clouds, to detect the emission from individual embedded stars, to determine the luminosity function into the substellar range - far below the hydrogen burning limit of about $0.08M_{\odot}$ - and to correlate star formation rates and stellar masses with the cloud properties. The spatial and spectral resolution available at far-infrared and submillimeter wavelengths will enable the detailed study of numerous infalling cores in nearby molecular clouds. It is believed that the infall halts abruptly at an accretion shock, which marks the boundary of the protostar or the protostellar disk. By detecting the IR spectral lines from these dust embedded accretion shocks, and measuring their profiles, the observations will probe the non-spherically symmetric infall onto the protostellar system and reveal how planet-forming disks are assembled.

The infall phase ceases when an outflow from the protostar impacts the infalling material, reversing its direction and sweeping it outward. The outflow is frequently collimated, by an as yet unidentified process, into a bipolar or jet-like flow. In the 1990's, IR imaging and proper motion observations will make it possible to see the jets and outflows as close as 10 AU from the protostar, thereby probing the agent of collimation. By observing the IR emission from the shocks produced when the outflow encounters ambient gas or protostellar disks, we will discover how the outflow evolves, how it inhibits infall, how it affects the disk, and how it interacts with the ambient molecular clouds.

How do protostellar and debris disks evolve?

Circumstellar disks are common features of stars of all ages. Theoretical models of the evolution of disks around protostars envision the growth of the disk by accretion, and the possible development of disk instabilities which cause material to spiral into the protostar or form a binary system. As the accretion phase ends, the dust in the (now) protoplanetary disk settles to the midplane, coagulates and forms planetesimals which ultimately may accumulate into planets. The forming planets sweep up the disk material near their radius and gravitationally interact with more distant material, producing "gaps" in the disk similar to those seen in the rings of Saturn. Finally, only planets, moons, asteroids and comets are left, and the occasional collisions of these larger bodies produce the leftover planetary debris disks observed around older stars, just as similar processes in our own solar system sustain the zodiacal dust cloud.

The infrared capabilities of the 1990's will allow us to image protostellar and protoplanetary disks around stars as distant as the Taurus cloud, and to detect gaps which may signal planetary system formation. The orientation of the disks can be correlated with the cloud core orientation and the magnetic field direction to improve our understanding of the dynamics of the collapse. Rotation curves can be measured and a composition profile derived for disks at all evolutionary stages, using resonantly scattered near-IR line emission for the inner disk and longer wavelength emission for the outer disk. Evidence for dust coagulation as a function of distance from the protostar will follow from spatially-resolved continuum spectroscopy at mid-ir wavelengths.

The final stage in the evolution of the protoplanetary disk is the planetary debris stage. IRAS found that a large fraction, certainly more than 20%, of mature main sequence stars near the Sun possess orbiting solid material. Prime examples are the disks orbiting the stars Vega, Epsilon Eridanus and Beta Pictoris. These disks, which are composed of particles much larger than typical interstellar grains, remain the best evidence for the occurrence of planetary systems around other stars. In the next decade, we should be able to detect disks similar to that around Vega around tens of thousands of stars out to distances of several kpc, to resolve a zodiacal cloud similar to the Sun's for the nearest stars, and to obtain detailed images of disks - searching for interior voids which may signal the presence of planets. Determination of the composition of the disk material and the size and frequency of voids as a function of the age and other characteristics of the central star will provide strong constraints on the processes, mechanisms and time scales for planet formation.

The study of the origin, evolution, and prevalence of extra-solar planetary systems will be complemented by the continued investigation of our own Solar System, particularly the region beyond the orbit of Jupiter. The spectral coverage and sensitivity of the infrared instrumentation of the 1990's will permit the study of all classes of objects in the outer solar system - not only the outer planets and their large satellites but also comets and the minor satellites, which may be better samples of the primordial material of the outer solar system. Infrared spectroscopy of the atmospheric gases and the surface ices of these primitive objects will provide critical information concerning the composition and physical conditions in our own protostellar nebula.

How prevalent are Low Mass Objects and Brown Dwarfs?

Infrared observations will not only detect the gaps in disks which signal the presence of planets, but also can provide direct measurements of young giant planets and of brown dwarfs of all ages and masses. These substellar objects range in mass downward from $0.1 M_{\odot}$ to planetary masses of order $0.001 M_{\odot}$ (about the mass of Jupiter). The number and distribution of such objects with mass smaller than the smallest star is unknown, but their abundance and properties may answer important questions about the formation of stars and planets, about the behavior of matter at high pressure, and even about the missing mass in astrophysical systems. Infrared observations are uniquely capable of detecting thermal emission from not only substellar companions but also isolated substellar objects, which glow faintly in the infrared as their residual heat of formation diffuses away. Isolated brown dwarfs can be detected in nearby space, in molecular clouds and stellar clusters, and, possibly, in the halos of other galaxies.

IV. TECHNICAL OVERVIEW

The IR spans three orders of magnitude in wavelength from 1 μm to 1000 μm . Over this very large span, the experimental techniques, the properties of the atmosphere, the telescopes, and the detectors all change dramatically.

In the **near-IR** (1 μm to 2.3 μm), observations can be made from the ground through three "windows" in the earth's atmosphere. Telescope and instrument techniques are quite similar to those developed and deployed at optical wavelengths, except that detectors are hybrid arrays using exotic infrared sensitive detector material like InSb or HgCdTe bonded to silicon readout devices. The recent revolution in this IR array technology enables a wealth of new scientific opportunities. At near-IR wavelengths, two near-term opportunities are highlighted in this report; the revitalization of existing telescopes with state-of-the-art instrumentation, including adaptive optics, and the 2 μm All-Sky Survey, 2MASS.

Near-IR observations from the ground are limited by airglow background, atmospheric absorption and atmospheric "seeing". The second generation near-IR instrument under development for the Hubble Space Telescope (HST), NICMOS, will exploit the absence of airglow emission and atmospheric absorption and seeing to make high sensitivity diffraction limited imaging and spectroscopic observations in the 1 μm to 2 μm range.

In the **mid-IR** (2.3 μm to 30 μm) ground-based observations are possible through four windows, but thermal emission from the atmosphere and from an ambient temperature telescope creates an enormous photon background against which observations must be made. A cryogenically cooled telescope operating outside the earth's atmosphere, like IRAS, COBE and SIRTf, is free from the limitations of atmospheric and telescope emission and atmospheric absorption. The natural mid-IR background in space, which originates from interplanetary and interstellar dust grains, is at least a million times fainter than that at any groundbased observatory; SIRTf's sensitivity is limited only by the statistical fluctuations in this natural background. Because SIRTf uses modern IR array technology, this facility has the power to transform our understanding of the basic questions of astrophysics. SIRTf is the cornerstone of IR astrophysics for the 1990's and beyond.

There are, however, some significant strengths of ground-based and airborne observations in the mid-IR; these include ready access to instrumentation, and large collecting area - useful both for light-gathering power for spectroscopy and for higher (diffraction limited) spatial resolution.

Modern mid-IR astronomy began in the 1960's with the introduction of the LHe cooled Ge bolometer on ground-based telescopes. Ground-based observations in the 2 μm to 30 μm atmospheric windows have evolved using adaptations to optical telescopes, progressing to the point that now most major optical telescopes incorporate some level of IR capability, although use of such facilities is generally compromised by inadequate IR adaptation or an inferior site for IR observations or, most frequently, a combination of both. In order to minimize the thermal emission, the telescope configuration and optics must be "optimized" for thermal IR observations, and the site selected to minimize the atmospheric absorption and emission. The recommended 8-m IRO is a unique IR optimized telescope on the best IR site known, the summit of Mauna Kea.

There is only a single large U.S. telescope dedicated to IR observations; the 3-m Infrared Telescope Facility (IRTF) on Mauna Kea, operated as a national facility by NASA's Planetary Exploration division. The upgrade of this facility to exploit the IR potential of Mauna Kea would create major new scientific opportunities for a large community and should be pursued aggressively and rapidly.

In the **far-IR** (30 μm to 300 μm) the earth's atmosphere is essentially opaque. As in the mid-IR, the residual atmosphere and telescope are strong sources of background emission. SIRTf is an extremely powerful observatory throughout this wavelength range.

Observations in much of this spectral regime and at many of the other infrared wavelengths obscured from the ground can be made from stratospheric platforms. NASA's airborne astronomy program began in the late 1960's, highlighted by deployment of a 0.3-m telescope in a Lear jet and the development of the KAO, a 0.9-m telescope in a C-141, in 1974. The KAO has been very successful for the past 15 years, providing critical observations ranging from stellar occultations at optical wavelengths to the study of collapsing clouds at 300 μm , but is now becoming scientifically outmoded because it can study only a small fraction of the IRAS sources. The recommended airborne observatory, SOFIA, which will replace the KAO, is key to the development of airborne infrared astronomy, providing a powerful and flexible facility for scientific observations in this field, capable of detailed study of all the IRAS Point Source catalog objects, and permitting development and deployment of state-of-the-art instrumentation.

Extrinsic germanium photoconductors provide the most advanced detector technology for far-IR wavelengths, used either as individual detectors or in small arrays. Low temperature bolometer arrays are also under development, particularly for use beyond 120 μm , and high frequency heterodyne receivers are becoming available at the longest wavelengths.

In the **submillimeter (300 μm to 1000 μm)**, observations are again possible from the ground through four windows whose transparency is a strong function of water vapor content; the longer wavelength windows have higher transparency. Telescope and receiver techniques are often extrapolated from radio wavelengths. Novel heterodyne components and more precise surface figures for telescopes than are commonly achieved at radio wavelengths are required. Thermal emission from the atmosphere and telescope, while still by far the dominant sources of background, are less important for high resolution spectroscopy, and telescope diameter is important for photon gathering and improved diffraction-limited angular resolution.

Submm observations with the 10m Caltech Submm Observatory (CSO) on Mauna Kea have demonstrated the viability of astronomical observations in the atmospheric windows at 600 μm and 800 μm using extrapolation of radio techniques. Already the findings of submillimeter water vapor masers and high velocity molecular outflows in evolved stars have demonstrated the importance of such observatories. Additional submm facilities currently under development, including the 10-m submm telescope for Mt. Graham, the Submm Array Interferometer under development by SAO, and the South Pole Submm telescope are expected to establish the basis for future ground-based developments in the submm wavelength range down to 350 μm .

Freedom from atmospheric absorption is a strong driver toward airborne or space-based platforms. SOFIA will provide an excellent platform for exploratory submm observations and instrument development. However, critical molecules like H_2O and O_2 cannot be observed from within the earth's atmosphere, even at airborne altitudes, because of telluric absorption. A small submm explorer, the Submillimeter Wave Astronomy Satellite (SWAS), is currently under development and expected to be launched in 1994. This mission, the first dedicated to high spectral resolution submillimeter observations from space, will study the Galaxy in spectral lines of H_2O and O_2 . The recommended Submm mission (SMMM) exploits the complete freedom from telluric absorption of the space environment, to provide our first unbiased spectroscopic view of the submm regime, while SIRTf will provide the most sensitive submm continuum measurements out to 700 μm .

Antartica offers an intriguing possibility for a ground-based astronomical site with conditions of atmospheric water vapor content and ambient temperature that are much more favorable to IR observations even than those of Mauna Kea. A small submm facility, ASTRO, is currently under development to evaluate the submm potential of the South Pole and a similar scale experiment, SPIREX, is proposed to investigate the potential of the South Pole for observations around 2.4 μm . These small scale projects are ideal for addressing such issues as seeing, operability, atmospheric conditions and IR background levels, which must be well understood in order to evaluate the potential of this site for a major IR observatory.

V. PROJECT RECOMMENDATIONS

Table 1 summarizes the projects recommended in this report. The project recommendations and descriptions following this table are presented in the same order as they appear in the table. Current estimates of the project development costs are included; in the cases of international participation, the U.S. costs are shown.

TABLE 1. PROJECT SUMMARY

CATEGORY	PROJECT	CATEGORY PRIORITY	START TIMES DEVELOPMENT OPERATION	COST (FY89\$)	
SPACE PROJECTS					
<u>MAJOR</u>	SIRTF	1	1993	1999	1.3B
<u>MODERATE</u>	SOFIA	1	1992	1997	230M
	SMMM	2	1995	1999	125M
<u>SMALL</u>	LAB/ASTR AUGMENTATION	1	1991		8M
GROUND-BASED PROJECTS					
<u>MAJOR</u>	8M IRO	1	1993	1998	80M
<u>MODERATE</u>	DETECTOR/INST DEVELOPMENT	1	1992	1993	50M
<u>SMALL</u>	2MASS	1	1992	1993	5M

A. SPACE PROJECTS

We very strongly recommend that the highest priority for astronomy in the 1990's be the development and operation of the Space Infrared Telescope Facility (SIRTF), the culmination of NASA's Great Observatories program.

The SIRTF observatory consists of a 1-m class cryogenically cooled telescope mounted on a free-flying spacecraft in high earth orbit. SIRTF will be operated as a national facility, with more than 85% of the observing time during its five year life time available to the community. SIRTF will achieve a one hundred to ten-thousand-fold improvement in sensitivity over current infrared capabilities. This gain, coupled with the imaging and spectroscopic power inherent in its large-format infrared detector arrays, will make SIRTF unique for the solution of key astrophysical problems ranging from the doorstep of the solar system to beyond the horizon of our current understanding.

SIRTF will be equipped with instruments utilizing modern two dimensional infrared arrays providing wide-field and diffraction limited imaging and spectroscopic capability over most of the IR spectral regime. SIRTF's cameras will provide imaging capability from 2 μm to 200 μm and photometry from 2 μm to at least 700 μm . SIRTF's spectrographs will cover the wavelength region 2.5 μm to 120 μm at low spectral resolution ($R=100$), and the 4 μm to 200 μm region at higher spectral resolution ($R=2000$). The sensitivity will be limited over most of this wavelength range only by the natural backgrounds in space, allowing SIRTF to achieve sensitivity gains of 100 to 10,000 over present capabilities. SIRTF will be launched by a Titan IV-Centaur into a circular orbit at an altitude of 100,000 km. The five-year lifetime will permit follow on studies with SIRTF itself of the many new scientific questions which will be posed by SIRTF's own discoveries, while an archival research program will make the SIRTF data accessible to the scientific community long after its data acquisition phase ends.

SIRTF has been under active study by NASA for more than a decade. The key technologies have been demonstrated; all that awaits is to build and launch this premier mission of the 1990s. With a development start in FY 1993, SIRTF can be launched by the year 2000, allowing a significant period of time for coordinated observations with NASA's other Great Observatories, HST and AXAF.

SIRTF's sensitivity increase, combined with the power of the detector arrays, achieves extraordinary gains in capability (Figure 2), one-million fold or more over the current state of the art in the infrared, and one-thousand fold or more over the performance anticipated for the ISO mission (planned for launch by the European Space Agency in 1993).

SIRTF SCIENCE HIGHLIGHTS

SIRTF will make fundamental contributions to virtually all contemporary forefront astrophysical problems. As illustrated in Figures 3 and 4, SIRTF will permit detection and identification of objects as disparate as galaxies at redshifts $z > 5$ and brown dwarfs in the solar neighborhood; and detailed study of problems as different as the relationship between high luminosity infrared galaxies and quasars, and the nature of planetary system debris around nearby stars. The investigations will reshape our understanding of processes ranging from galaxy formation in the early universe to the formation of our solar system.

The identification of the epoch of first star formation in galaxies is critical to our understanding of the process of galaxy formation. Once a very young galaxy reaches an age of tens of millions of years after its first stars are formed, much of its luminosity is produced by cool red giant stars emitting a broad spectrum peaked at $1.6 \mu\text{m}$. SIRTF can identify this near-infrared peak redshifted to longer wavelengths; for example, SIRTF can detect a young galaxy of average mass at redshift $z=5$, seen when the universe was less than 10% of its current age. An object of high redshift which shows no evidence for the peak is a candidate for identification as a galaxy still forming its first generation of stars.

In some ultraluminous infrared galaxies, bursts of star formation account for nearly all of the observed luminosity, but others appear to harbor dust-enshrouded quasars. SIRTF's imaging surveys will trace the evolution of quasars and ultraluminous infrared objects to redshifts well in excess of 5. Low resolution infrared spectra can identify characteristic features due to emission from dust and gas and determine the redshift, and hence the luminosity, of the infrared-bright objects. These studies will determine how both the absolute and the relative number of starburst galaxies and dust-enshrouded quasars varies with epoch and determine how the cosmic evolution of this population compares with that of the optically and radio selected quasars to which they may be related.

Brown dwarfs more massive than Jupiter and less massive than the $0.08M_{\odot}$ required for a star to sustain nuclear hydrogen burning are expected to be visible in the infrared as they radiate the heat generated by their gravitational contraction. SIRTF's sensitivity will be such that objects with 10-30 Jupiter masses and ages less than 10^7 years can be detected out to the Taurus cloud. SIRTF can also discover older, less luminous brown dwarfs through deep imaging of nearby star clusters, unbiased surveys, or through targeted searches for companions of nearby stars.

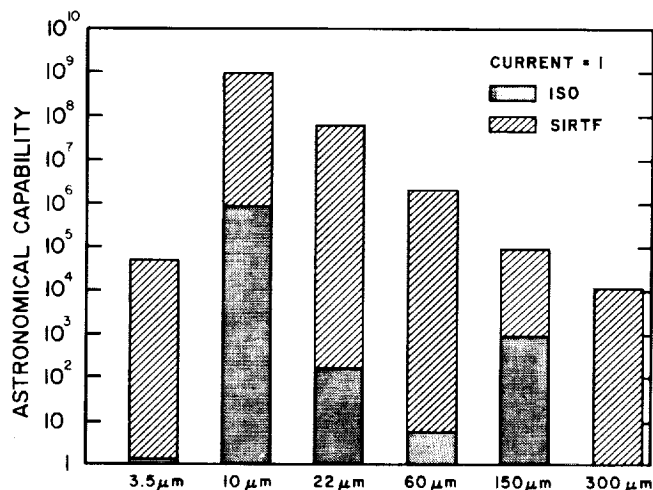


Fig. 2. Astronomical capability is defined as lifetime * efficiency * # pixels / (sensitivity)². Current capabilities are defined by IRTF, KAO and IRAS performance. Predictions for ISO and SIRTF use published data.

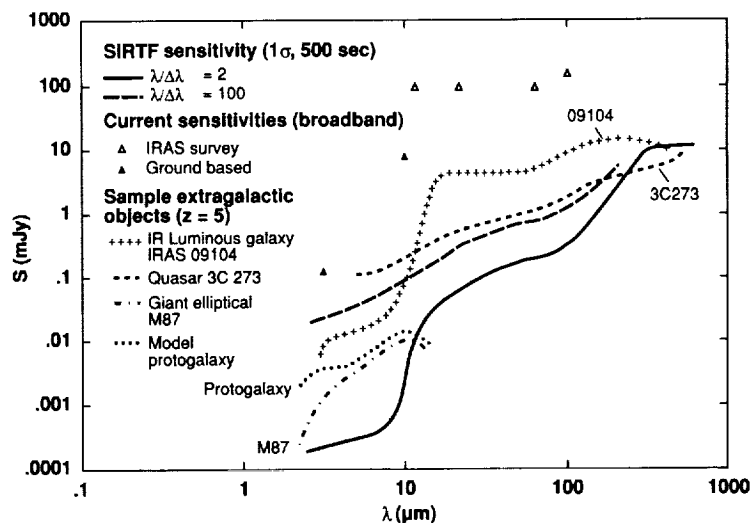


Fig. 3. The enormous sensitivity of SIRTF is shown by comparison with the expected brightness of a variety of classes of extragalactic sources at $z=5$.

Zodiacal clouds like the Sun's can be imaged by SIRTf around the nearest solar-type stars, while planetary debris disks like those found by IRAS can be studied around stars more distant than 1kpc. For the more prominent systems, SIRTf's images will show the orientation, structural features, and detailed morphology of the disks, including the inner dust-depleted regions suggestive of planets orbiting within the disk. Low resolution spectra of the debris - in both reflection and emission - will provide critical diagnostics for studies of composition, replenishment, and origin of the material.

Just as SIRTf can study material in the outer regions of other solar systems, it will extend the studies of the outer regions of our own Solar System. The ices and gases that condensed in the collapsing solar nebula further than 5 AU from the Sun, and that are now locked in the comets and planetary satellites, carry the chemical and physical history of the primitive solar nebula in the zones where the outer planets formed. SIRTf can obtain detailed spectra of the gaseous and solid materials in this distant zone; tracing the primitive solar nebula in this fashion will permit us to combine knowledge of the early solar system with the observed properties of stars in formation to understand more fully the formation of solar systems.

SIRTf will also conduct surveys: Some of these will be targeted at specific scientific problems - searches for candidate protogalaxies, for distant Kuiper belt comets in the ecliptic plane, or for embedded protostars in dark clouds in the Galaxy. Others will be totally unbiased, deep surveys aimed at searching for the as yet unnamed and unimagined phenomena which will lie within SIRTf's vast new horizon. SIRTf's spectrograph will be used extensively not only for followup observations of objects discovered in the imaging surveys, but also for complete infrared spectroscopic surveys of known classes of objects. These surveys and the archive of SIRTf's targeted observations will represent a legacy for astronomical study long after the end of the SIRTf mission.

We recommend the immediate development of SOFIA, a joint NASA-Federal Republic of Germany airborne observatory for infrared astronomy.

SOFIA is a 2.5-m telescope system mounted in a modified Boeing 747 aircraft. Flying over one hundred 8-hour missions per year at altitudes of 41,000 feet, above 99% of the water vapor in the earth's atmosphere, SOFIA will provide the astronomical community routine observations at most infrared wavelengths inaccessible from the ground. SOFIA's tenfold increase in collecting area over the KAO will enable study of any of the sources in the IRAS Point Source Catalog. A great strength of SOFIA is its flexibility: frequent access to the near space environment, realtime hands-on access and rapid interchange of focal plane instruments, and round-the-world deployment capability. SOFIA provides an excellent platform for the development of advanced instrumentation and for the education and training of the next generation of experimentalists.

SOFIA is a joint project, with the Federal Republic of Germany supplying the telescope system, supporting the operations at roughly the 20% level, and participating in the flight program at a similar level. NASA and the German Science Ministry (BMFT) have successfully completed preliminary design studies for SOFIA. A development start for SOFIA in FY1992 would allow observations to begin in 1997.

SOFIA SCIENCE HIGHLIGHTS

SOFIA's capability for diffraction-limited imaging beyond 30 microns and for high resolution spectroscopy over the entire 1 μm to 1 mm infrared band will allow studies of the composition, structure, and dynamics of planetary atmospheres, comets, and interstellar gas and dust; the initial luminosity function of stars embedded in nearby molecular clouds; the infall and outflow from protostars; and the nature of the luminosity sources in nearby starburst and AGN galaxies.

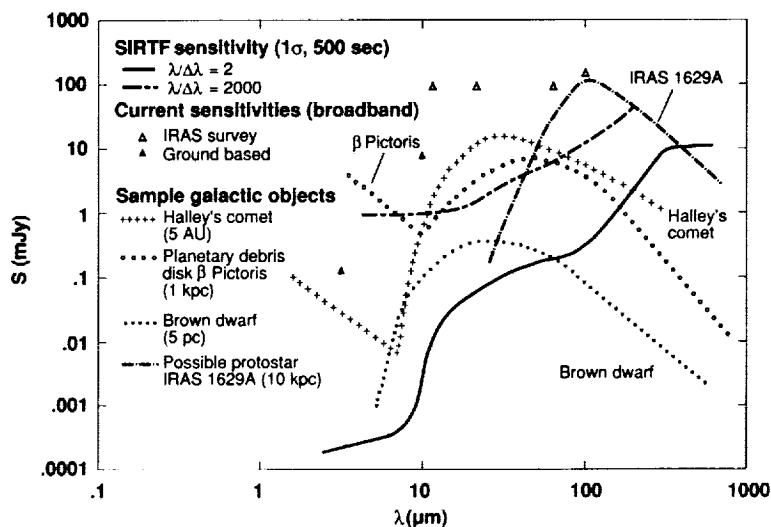


Fig. 4. SIRTf sensitivity to Galactic and Solar System sources.

Far infrared observations with the spatial resolution of SOFIA will probe the distribution and nature of the embedded luminosity source(s) in the nuclei of nearby galaxies. Our own galactic nucleus may provide valuable clues to the phenomena occurring in galactic nuclei. Far infrared polarimetry and spectroscopy will map the magnetic field distribution and gas dynamics in the 2-10 pc ring of gas and dust surrounding the center of the Galaxy, possibly a magnetic accretion disk from which material spirals into the galactic center.

The bulk of the luminosity from protostars generally emerges in the 30 μm to 300 μm band (illustrated in figure 5), so only far infrared observations can measure the bolometric luminosity. SOFIA has the sensitivity to detect 0.1 L_{\odot} embedded stars at distances as large as 500 pc. SOFIA's far IR spatial resolution enables studies of the luminosity function characterizing solar or subsolar mass stars in nearby star forming regions like Taurus. Resolved maps of the infrared continuum and line emission from individual protostellar sources determine the dust and gas density distribution around the protostar and the nature of the protostellar infall and outflow. Far-IR high spatial and spectral resolution observations of protostars in Taurus will measure the accretion shock spectrum and provide the definite detection of infall and accretion in low mass protostars.

The high spectral resolution capability of SOFIA is also necessary for the determination of the composition and dynamics of interstellar and solar system gas. The ability to detect characteristic molecular lines, such as the high rotational lines of CO and rotational transitions in H_2 , is often limited by a small line to continuum ratio, and so high resolving power dramatically improves the sensitivity of the line measurement.

Compositional studies range from mapping the elemental abundance variations in ionized and atomic gas in nearby galaxies, to determining the abundances of the major reservoirs of C, N, and O and the state of oxidation of the primitive solar nebula during the epoch of star formation through observations of comets. The unique capability of an airborne observatory to track occultations will allow absorption measurements of, for example, the structure of the atmosphere of Pluto, one of the few large planetesimals remaining in the solar system. An improved understanding of the primitive chemical processes of the outer solar system will translate directly into an improved perception of the processes at work in other solar systems and an understanding of how representative is our own solar system.

We recommend the Submillimeter Mission (SMMM), an innovative new mission for the Explorer program.

The Submillimeter Explorer utilizes a 2.5-m ambient temperature telescope with a liquid-helium cooled complement of instruments designed to obtain complete submillimeter spectra from 100 μm to 700 μm for a large number of galactic and extragalactic sources. SMMM will provide our first complete, unbiased spectroscopic view of the submillimeter portion of the electromagnetic spectrum.

Key elements of the SMMM technology program are well underway, and must be continued in the near term to be ready for a timely development phase in the mid-1990's. The areas of technology development that require support now are extending heterodyne receivers to wavelengths as short as 300 μm , and development of lightweight panels that can meet the high surface accuracies required for diffraction limited performance at 100 μm . The SMMM represents a substantial opportunity for a joint project with the French Space Agency, CNES, and also possibly with ESA. The SMMM could be pursued either as an Explorer class mission or an expanded moderate mission, depending on the results of the current Phase A studies, and the extent of the international collaborations that are finally negotiated by the interested parties.

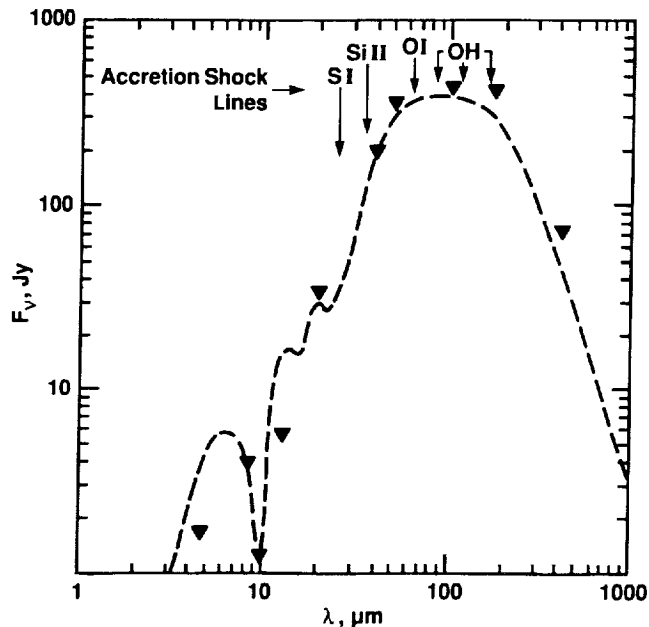


Fig. 5. The energy distribution of the possible protostar L1551 in the Taurus molecular cloud. The wavelengths of lines relevant to the study of accretion shocks are indicated.

SMMM SCIENCE HIGHLIGHTS

SMMM will probe the origins of stars and the chemistry of the interstellar medium, and will obtain a complete spectral atlas for molecules, atoms and ions in the 100 μm to 700 μm range in a wide variety of galactic and extragalactic sources. Complete submillimeter spectra of clouds of gas - ranging from quiescent atomic clouds, to dense cold clouds, to collapsing clouds, to those clumps containing protostars - will probe the critical chemistry, dynamics, heating, and cooling processes that occur in the gas and dust before and during gravitational collapse. Submillimeter spectra of nearby galaxies will provide the basis for global comparative studies of star formation, interstellar chemistry, and cooling processes.

These spectra will enable studies of chemical and isotopic abundances and hydride molecules for metals to atomic number of 30 or more, including the cosmologically significant species such as HD and LiH, and be able to examine their variation with position within the galaxy. SMMM will observe the carbon reservoir species CO and C₂ and the oxygen reservoir molecules H₂O and O₂ in a wide variety of gas phase environments, and identify dominant large molecules and small dust grains by observations of vibration-rotation spectra of large linear-chain and polyacetylene molecules and of vibrational modes of polycyclic-aromatic-hydrocarbon dust grains, thus examining the link between the lighter molecules observed at millimeter wavelengths and the small dust grains discovered at shorter infrared wavelengths.

In star formation regions, SMMM will enable thermal balance studies in dense protostellar environments and molecular shock regions where H₂O and hydride molecules dominate the cooling process. SMMM will enable studies of protostellar infall by observations of line absorption against continuum emission from dense cloud cores.

We recommend that the laboratory astrophysics program be substantially augmented in the 1990's.

Understanding the IR observations of the 1990's will require, as input, fundamental data describing the properties of atoms, ions, molecules, and dust grains. It is frequently the case that the largest uncertainties in theoretical models are due to uncertainties in these data, rather than to approximations inherent in the models. These essential data are provided in some cases by theoretical atomic, molecular, or condensed-matter physics, but predominantly by laboratory astrophysics. Laboratory astrophysics must be recognized as a special interdisciplinary area which requires significantly higher levels of support for the 1990s, with funding made available for laboratory start-up programs and for graduate students and postdoctoral fellows.

Atomic, ionic, and molecular spectral lines in the IR will offer a wealth of information concerning chemical and isotopic abundances and the physical conditions in the gas, but interpretation of this spectral data will require substantial progress in atomic and molecular astrophysics. Even for the most simple and fundamental molecule, H₂, there are great uncertainties regarding the cross sections for collisional excitation of the vibration-rotation levels from which we observe emission. Collisional cross section data for many isotopic species of stable molecules, as well as molecular spectroscopic data for highly reactive molecules and ions, are needed. There are currently scant laboratory data on highly vibrationally-excited states of molecules, radicals, and ions or on the larger organic molecules and ions which bridge the gap between the molecules observed in the radio and the polycyclic aromatic hydrocarbon (PAH) macro-molecules and small grains seen in the near-IR.

Most of the mid- to far-infrared radiation in the universe originates from interstellar dust grains. Both laboratory and theoretical work is needed on the physical properties of candidate grain materials, in order to interpret absorption, emission, and polarization measurements. The study of small grains, whose sizes (5 to 30 Å) put them in the transition region between large molecules and bulk grains, is especially important. For example, the optical properties of PAH clusters, and of hydrogenated amorphous carbon (HAC), require careful laboratory study in order to permit interpretation of the infrared emission features seen from interstellar dust clouds. Laboratory spectroscopy of mixed molecular ices of astrophysical interest is another area of high importance to the study of the origin and evolution of solid matter in interstellar clouds and in the solar system.

B. GROUND-BASED PROJECTS

We recommend the immediate construction of a national infrared-optimized 8-meter diameter telescope on Mauna Kea.

From this remarkably dry and stable site, by the use of modest adaptive optics techniques, IRO will exceed the sensitivity of a conventional 8-m telescope by more than an order of magnitude and will achieve diffraction

limited performance of 0.07 arcsec at 2.2 μm . Within all atmospheric windows from 1 μm to 30 μm the telescope emission will add only minimally to that from the atmosphere itself, producing the most sensitive measurements from the ground at these wavelengths where sharpest imaging is naturally achieved.

The technical requirements for the IRO are well understood, and can be met by extension of the design for the NOAO 8-meter telescopes. The telescope must deliver a final image of less than 0.1 arcsec diameter. To minimize radiation from the telescope itself, the mirrors must be coated with a material of lower emissivity than aluminum, probably silver. Some adaptive optics capability will be routinely required, but even simple wavefront tilt compensation will allow imaging at a resolution of 0.1 arcsec. The choice of site is crucial: Mauna Kea is recognized as the best IR site in the world.

We note also that, as recommended earlier, the NASA IRTF, the dedicated 3-meter infrared telescope located on Mauna Kea, is the logical location at which to take the earliest advantage of infrared optimization techniques.

IRO SCIENCE HIGHLIGHTS

IRO will provide a level of clarity in imaging never before achieved from the ground, with angular resolution in the near IR an order of magnitude sharper than typically obtained at optical wavelengths. Infrared images of planets, satellites, comets and asteroids will reveal the composition and structure of surface and atmosphere, and can be used to monitor temperature variations or other changes, for example the volcanic activity on Io.

The IRO will enable detailed imaging and spectroscopic observations of forming stars in many nearby star formation regions, such as Taurus, Ophiuchus, Orion and NGC2264. Studies of the structure, energetics and composition of protoplanetary disks around young stars, with a spatial resolution of 10 AU in the nearest star-forming regions, will allow detailed characterizations of the disks and may show condensations or voids where planets are in the process of forming.

IRO will measure three dimensional motions for hundreds of stars within the central parsec of our Galaxy through a combination of proper motion and spectroscopic studies to an accuracy of 10 km/sec, and so provide a critical test for the presence of a black hole. IRO may even be able to measure directly the velocity of the gas rotating around such a massive object or to detect emission from a black hole accretion disk.

Perhaps IRO's greatest contributions will arise from its abilities to study distant galaxies as they first form stars in the early Universe. Models indicate that young galaxies at redshifts exceeding 5 should have 2.2 μm magnitudes in the range 22 to 24, and so be readily accessible to IRO; the deepest 2.2 μm image currently available (with a 5-sigma threshold of 21.5 mag) already contain galaxies not detected at optical wavelengths (figure 6). IRO can obtain detailed images of such galaxies, and measure spectra of them and other extremely distant examples discovered by SIRTf, in order to determine their morphology, redshift, composition, and ionization state.

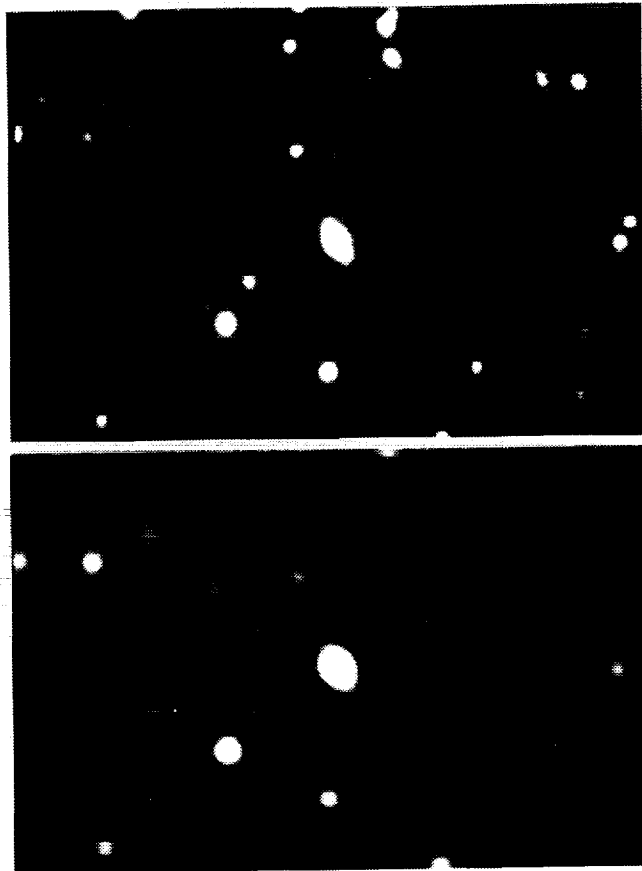


Fig. 6. A deep 2.2 μm image (lower panel), with a 5 sigma threshold 21.5 mag, reveals faint red galaxies not detected in the deep I-band image (upper panel). Courtesy of L. Cowie, Univ. of Hawaii.

We recommend a strong program to develop and evaluate IR array detectors and to deploy the best of these arrays in state-of-the-art instruments for existing telescopes.

Infrared array technology in the wavelength range from 1 μm to 30 μm is evolving very rapidly, and substantial development and evaluation work is needed to exploit this technological revolution. The technology involved has been largely developed as a result of the high interest in 1 μm to 30 μm IR arrays by the Department of Defense. NASA has carefully nurtured detector development activities both for SIRTf and for NICMOS, the infrared instrument on HST. It is extremely important to continue the testing and understanding of the properties of these arrays in order to maximize the scientific return from HST and SIRTf.

Currently, high quantum efficiency, low read noise, low dark current arrays are available in formats up to 256x256 in the wavelength range 1 μm to 5 μm . Of critical concern in this wavelength range is to extend the format to 512x512 pixels; an array of this size is at the edge of current technology evolution, and is feasible within 5 years. Arrays of comparable quality for the thermal infrared from 5 μm to 30 μm in formats of 128x128 or even 256x256 pixels are also within reach. Of particular concern for ground-based and airborne observations is the need for high speed, low-noise readouts for large format arrays working beyond 3 μm , where the thermal photon background from the atmosphere and ambient temperature telescopes becomes very high.

The heart of any observatory is its complement of instruments. Those that utilize the finest state-of-the-art detectors maximize the scientific return. Ground-based telescopes can be reborn, increasing observing efficiencies by orders of magnitude, with the introduction of new array based cameras and spectrometers. **We urge the NSF to assist observatories in procuring and deploying the best of the infrared arrays** for new generations of focal plane instruments. A particularly exciting opportunity enabled by modern IR arrays is the ability to systematically survey substantial areas of the sky with high sensitivity and efficiency. One particular survey, an all-sky broadband near IR survey, is highlighted in this report. There are other, more specific, surveys that are also of high scientific interest; for example deep images of large or unusual galaxies, galactic surveys in the H_2 lines around 2 μm or in the Brackett gamma line of HI at 2.16 μm , and very deep multicolor IR surveys for the faintest extragalactic objects.

Another compelling opportunity for the 1990's is the application of adaptive optics to ground based telescopes to correct continuously for the effects of atmospheric turbulence. Existing telescopes equipped with adaptive optics can address new questions while new large telescopes can be utilized to obtain images in the 1 to 5 μm range with unprecedented clarity. Adaptive optics has been substantially developed within the defense community and NSF has taken the lead in providing the astronomical community access to this technology. The complexity and cost of adaptive optics is much reduced at IR wavelengths because of reduced bandwidth requirements, relaxed reference star requirements and increased correlation sizes at the longer wavelengths. Even a modest wavefront tilt correction can provide substantial image size improvements. The IRTF is particularly well suited for early implementation and utilization of this technology.

We recommend the immediate initiation of a 2 μm all sky survey (2MASS) to a level of sensitivity 50,000 times greater than that achieved by the 1969 Two Micron Sky Survey.

2MASS is a prime example of a modest project with a very large long term payoff. A pair of dedicated one meter class ground-based telescopes, one for each hemisphere, equipped with modern near-IR array detectors, can completely survey the sky at three wavelengths between 1 μm and 2.2 μm in less than two years, detecting an estimated 100 million sources. The 2MASS survey will explore the large-scale structure of the local Universe by mapping the distribution of galaxies to a distance of 100 Mpc over the whole sky. This survey will be relatively unaffected by dust obscuration in our own and other galaxies and is uniquely sensitive to those classes of stars which dominate the mass.

The survey will explore large scale stellar structure of the Milky Way Galaxy and address basic stellar evolution questions by measuring luminous evolved stars throughout the Milky Way, in the Magellanic Clouds, and other galaxies in the Local Group. 2MASS will dramatically expand our current census of the coolest stars and probe the young stellar population within dozens of dense molecular clouds. It will provide basic support to a variety of NASA missions of the 1990's by highlighting new questions and identifying new targets for the major IR missions, and supporting X-ray surveys through identification of x-ray sources with reddened stars, cool dwarfs, and AGN's.

Studies to define the survey hardware and strategy are currently underway. Data processing and survey product generation utilize NASA's Infrared Data Analysis Center (IPAC). Project development could begin as soon as 1991.

C. PERFORMANCE COMPARISON

Together SIRTf, SOFIA and IRO provide the astronomical community with extremely powerful capabilities over the entire infrared spectral regime. In this section, we attempt to quantify and compare the performance expected for these three facilities. Sensitivity estimates are 1 sigma in 500 sec.

Imaging and Photometry (Figure 7)

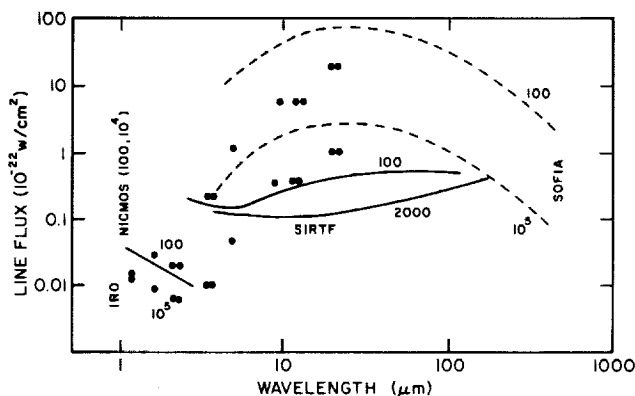
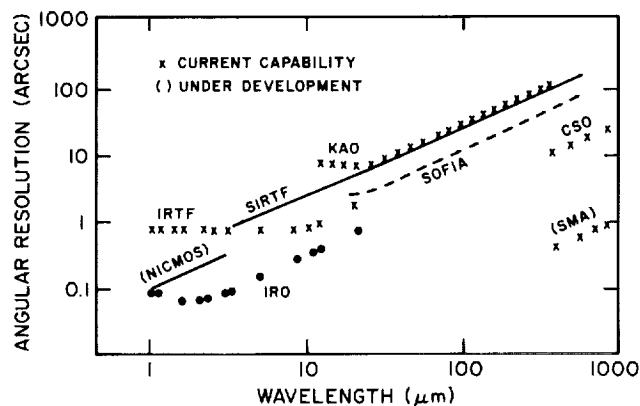
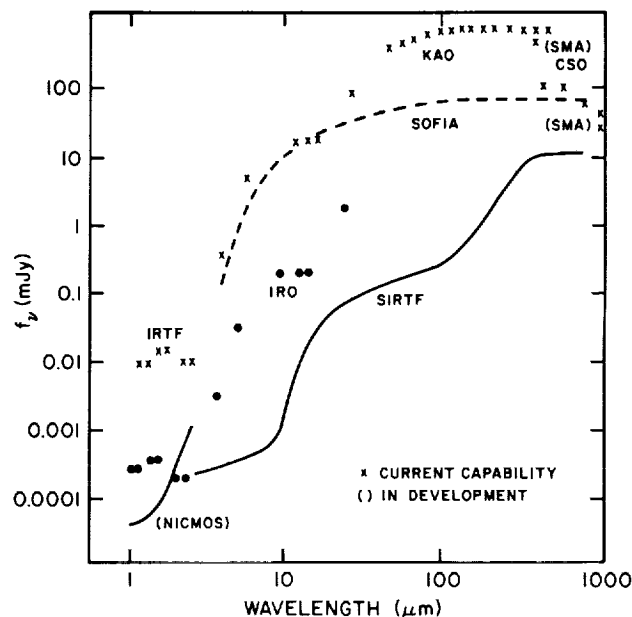
Over the entire $3\ \mu\text{m}$ to $700\ \mu\text{m}$ range SIRTf provides uniquely powerful and sensitive imaging and photometry capability, orders of magnitude more sensitive than any other facility, existing or proposed. SIRTf, together with the NICMOS instrument on HST provides superb imaging sensitivity from $1\ \mu\text{m}$ to $700\ \mu\text{m}$. The 8-m IRO offers more than an order of magnitude improvement in point source sensitivity over the current IRTF capability. SOFIA offers nearly an order of magnitude improvement over the KAO, and access to any of the IRAS PSC objects for detailed study. For studies of emission extended on a scale large compared to the angular resolution, SIRTf is some three orders of magnitude more sensitive than any warm telescope.

Angular Resolution (Figure 8)

SIRTf provides diffraction limited angular resolution beyond $3\ \mu\text{m}$. Because of their larger diameter telescopes, SOFIA and the 8-m IRO offer better diffraction limited capability. IRO provides the highest resolution imaging capability in the near IR windows of any ground-based optical or IR telescope, while SOFIA offers the highest available resolution in the IR bands inaccessible from the ground.

Spectral Line Sensitivity (Figure 9)

The performance is illustrated for a low spectral resolution of 100 and high resolution of 10^5 . In the $3\ \mu\text{m}$ to $200\ \mu\text{m}$ region, SIRTf provides the highest sensitivity to broad spectral lines, for example those expected for extra-galactic sources. In the $1\ \mu\text{m}$ to $30\ \mu\text{m}$ windows, the 8-m IRO offers unsurpassed spectroscopic sensitivity for narrow lines ($\Delta v \sim 1\text{km/sec}$) and very powerful capability for observing broad spectral lines in the near-IR. SOFIA offers flexible spectroscopic capability throughout the IR, particularly important at the longer IR wavelengths. SOFIA and the IRO can support the development of state-of-the-art spectrometers throughout their long lifetime. Again, it is assumed that the line source is spatially unresolved. For extended sources SIRTf offers very substantial additional advantages.



VI. FUTURE DIRECTIONS

This entire report is a testament to the huge rewards that follow directly from the deployment of optimized telescopes, from their equipment with state-of-the-art instruments, and from their location at sites with superior environmental properties. The way to the future must pursue those same strategies to ever higher levels of implementation.

Some long-term implications of this tripartite prescription are not difficult to deduce. On the ground, steps through modest pilot projects aimed at the eventual construction of IR imaging interferometers consisting of multiple telescopes; continued development and deployment of larger format array detectors; investigation of the possible use of Antarctica as an observing site. In space, larger single dishes and Lunar interferometers; longer lifetime refrigeration of larger format detectors; an orderly progression from low earth orbit, to high earth orbit, the Moon, and eventually to observatories located beyond the zodiacal cloud -- as distant from the Sun as Jupiter.

TABLE 2. FUTURE TECHNOLOGY RECOMMENDATIONS

PROJECT	PRIORITY	COST (FY89\$)
SPACE TECHNOLOGY		
FAR-IR/SUBMM PROGRAM	1	75M
GROUND-BASED TECHNOLOGY		
O/IR INTERFEROMETRY PROGRAM	1	20M

We recommend a moderate scale program of ground based IR interferometry development and demonstration for the 1990's.

This program would support current technology development activities, build at least one interferometric imaging array of 3x 2 meter telescopes adequate to undertake imaging interferometry in the near infrared and to evaluate the practical limits in the thermal infrared out to 20 μm , and establish the technical basis for planning a Very Large Optical/Infrared Array for the first decade of the 2000's

The next major development in 1 μm to 30 μm , ground-based astronomy is very likely to be imaging interferometry. IR imaging interferometry will provide orders of magnitude improved spatial resolution, and qualitatively new kinds of information from very high angular resolution imaging of forming stars and planetary systems, starburst galaxies, and active galaxy nuclei. Interferometric imaging will also allow progress on study of circumstellar environments (YSO's, evolved stars, novae, nebulae) with unprecedented resolution.

The technical basis for optical/IR interferometry is well developed, with such components as delay lines, correlators, fringe tracking servos, and active optics for rapid tilt and piston correction in use at the Mt. Wilson Mk III optical astrometric interferometer and the Berkeley Infrared Spatial Interferometer together with several smaller technology development projects underway in the U.S. The technical objectives of the decade program include construction, metrology, and control of small and medium aperture telescopes to required tolerances and optimization of correlation techniques as well as site testing for correlation time, isoplanatic angle, and interferometer specific parameters. The experience of radio astronomers in aperture synthesis carries directly over to optical/IR, with the same software in use for both wavelength regimes.

The recommended technology demonstration projects of the 1990's will offer milliarcsec or better imaging capability with limiting magnitudes for 2-m apertures and existing detector arrays of about 15 mag at 2.2 μm and 5.5 mag at 10 μm . The major ground based facility for the first decade of the 2000's, the Very Large Optical/Infrared Array, will offer full aperture synthesis imagery of bright and faint sources.

This program should be carried out largely in the university community, where intensive participation by students will be possible. At least some of the projects should involve several groups with a range of research and technical interests. The large facility of the 2000's will be a unique national or international resource, and should offer the access and support expected of a national facility.

All of the projects proposed for the decade in this panel report hold promise for exceptional scientific returns. To reach some dreams, however, such as imaging the accretion disk around a black hole, or viewing an earth-like planet within a few AU of another star, we must obtain a spatial resolution significantly better than a milliarcsecond for very faint sources. This cannot be done with ground-based interferometry in the optical and infrared. The only location with adequate thermal, mechanical and image stability for such an interferometer is the lunar surface. The individual telescopes that are part of such an array need not be large, and so the construction of an optical/infrared interferometer is feasible as an early project when humans return to the Moon. Demonstration of the crucial technologies for interferometry at these wavelengths is the essential first step which must be undertaken on the ground during the coming decade if astronomy is to be poised to act quickly when the opportunity arises to construct a lunar-based interferometer.

We recommend that the NASA program for phased exploitation of the far-ir/submillimeter wavelength range be vigorously pursued.

The Decade review report of the 1980s included a major 30 μm to 1000 μm project, the Large Deployable Reflector (LDR), designed to complement HST, large ground-based telescopes, and SIRTf. LDR was envisaged as a 10-m class, ambient temperature telescope to be erected in space from the Space Shuttle and operated in low earth orbit. It is now generally agreed that low earth orbit is undesirable for such a facility, that the technology is not ready for this mission, and that another approach is required. The mature perspective which led SIRTf to high earth orbit guides us to suggest that the correct path for submm astronomy in space will evolve via the 0.5m diameter Small Explorer mission SWAS, already in development, through a 2.5m class Explorer mission (the submillimeter mission SMMM), to a major project such as a 10-m to 20-m diameter telescope operated in high earth orbit or a Lunar far IR/submm interferometer.

In order to accomplish this plan, support is needed in the form of a technology development program aimed initially at bolometers and photoconductor arrays and heterodyne receivers in the far infrared, and at telescope panels required for the early missions. Large photoconductor detector arrays for the wavelength range 30 μm to 200 μm are necessary for both imaging and spectroscopic applications. Sensitive, low temperature arrays of bolometers should be developed for imaging continuum sources at wavelengths beyond 200 μm . Submm heterodyne receivers are several orders of magnitude away from theoretical performance limits. High frequency mixers, local oscillators and ultra-high bandwidth IF frequency components all require further development. Once theoretical noise limits are reached, receivers should be combined to form focal plane arrays. Large, lightweight panel structures capable of maintaining diffraction limited performance at wavelengths shorter than 100 μm are needed.

It is essential that the university community be heavily involved in this technology program, and that the developments have applications in near term missions. Continued research and development that capitalizes on developments in industry and university laboratories is critical to making the most of the space environment. In this context it is important that laboratory devices be incorporated into instruments that can be used on ground-based and airborne telescopes. Such instruments return valuable science, fill gaps between major missions, and uncover problems at a phase of development when the cost of fixing problems is modest.

Subsequently the technology program should be directed toward developing increasingly long lived cryogenic coolers for space, and assembly and control of larger or multiple structures in high earth orbit or on the Moon.

The fundamental performance limitation for any submillimeter space observatory is the size of the diffraction limited beam. Achieving spatial resolutions comparable to those obtainable at near infrared wavelengths with IRO would require a large filled aperture or multi-element interferometer with size or spacing exceeding 100 meters. The only site with the necessary stability for such a telescope is the lunar surface, on which there is no obvious limitation to the obtainable size. Cost limitations are set primarily by the mass of materials to be transported. The ultimate potential of submillimeter astronomy from the Moon is so great that technology development in the coming decade for detectors, relevant cryogenics, and lightweight telescope components is a sound investment to prepare the technology base for a lunar observatory.

VII. INFRASTRUCTURE

The 1990's will witness a tremendous leap forward in our knowledge of the infrared sky, a sky rich with information. We will be able to convert these observations into understanding if, and only if, a strong infrastructure is in place and well supported.

Theoretical Astrophysics

To a considerable extent, interpretation of astronomical observations involves comparison between the observations and predictions of theoretical models -- it is in this way that we infer the conditions present in remote regions of space and refine our physical understanding. The forthcoming explosion in IR imaging and spectroscopy will demand greater sophistication in the theoretical models. Theoretical progress is required on a number of overlapping fronts:

Improvements in our understanding of the local "microphysics" involved in heating, cooling, ionization, and chemistry in regions ranging from cool stellar atmospheres to diffuse interstellar plasmas. It is becoming increasingly important to develop the capability to compute realistic emission/absorption spectra, including detailed non-LTE excitation of many-leveled species such as H_2 and H_2O , and more detailed, but still approximate, treatments of larger species such as PAHs.

Accelerated work on the nature and formation/destruction of interstellar dust, and the important effects which dust grains exert on the interstellar medium, as well as improved understanding of the interaction of gas and radiation including the structure of photodissociation fronts, ionization fronts and X-ray heated regions.

Fluid dynamic modeling of the flows which occur in, for example: MHD shock waves; "turbulence" in molecular clouds; gravitational collapse of rotating, magnetized clumps in molecular clouds; accretion disks around protostars; outflows associated with star formation; and ionization-shock fronts formed when neutral clouds are exposed to ionizing radiation from newly-formed OB stars.

Global models that study the interplay between stars, gas, photons, and gravity which determines the structure of the interstellar medium in a galaxy, the rate of star formation, the initial mass function, conditions in starburst, interacting and merging gas-rich galaxies, AGNs, and QSOs.

It is imperative that adequate funding be provided to support a vigorous theoretical program.

Training and nurture of experimentalists

There is a grave risk that a program devoid of opportunities for young scientists at various stages of their careers will ultimately lack the senior people required to carry out major programs as they arise. Challenging opportunities providing "hands-on" experience are vital. Within infrared astronomy, both ground-based and airborne/spaceborne programs are required; the former can be provided through the support of a broad based instrument program and the latter through support of SOFIA and the balloon program. SOFIA will support approximately 40 investigator teams per year, including an on-going instrument development program. Small university groups will be able to carry out complete investigations on a short time scale at low cost. Balloon-borne telescopes will be an essential component of the next generation of CMB anisotropy experiments at near-mm wavelengths. In principle, maps of the CMB anisotropy with $\Delta T/T \sim 10^{-6}$ can be made in a single balloon flight. SOFIA, the ground-based instrument development program, and the balloon program offer excellent test-beds for new detectors and receivers, and an excellent training ground for young scientists.

Data Analysis and Archiving

The creation of an entire branch devoted to Mission Operations and Data Analysis demonstrates a commitment within NASA to a data reduction and analysis effort commensurate in scope with that of the project which generates the data. This level of support should become the standard for all of astronomy.

A strong archival data analysis program allows a large, broadly distributed community to participate in forefront astronomical research. An excellent model is provided by the Infrared Processing and Analysis Center (IPAC), which was established to process the data from the IRAS mission, generate and verify the scientific products and to support the community in the utilization and analysis of the data products. IPAC has been very successful in supporting broad community participation in the analysis of the rich IRAS data base. The IRAS database will continue to be a vital resource for the astronomical community. In the future, the COBE, ISO and SIRTf data should be available for archival interdisciplinary study. Large, extremely well characterized data bases from selected ground-based observations, e.g. survey data, should also be considered for inclusion in the archival program.

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